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Temporal shifts in reef lagoon sediment composition, Discovery Bay, Jamaica

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Abstract

Discovery Bay, north Jamaica, forms a large (1.5 km wide), deep (up to 56 m) embayment that acts as a sink for reef-derived and lagoonal carbonate sediments. Since the mid-1960s, the bay has also provided a sink for inputs of bauxite sediment that are spilled during loading at a boat terminal constructed within Discovery Bay. Bauxite has accumulated across much of the southern section of the bay with surficial sediments presently composed of up to 35 weight% non-carbonate. Cores recovered from sites on the western side of the bay provide a stratigraphic record of this history of bauxite contamination across water depths from 5 to 25 m. The bauxite-influenced upper sediment horizons are clearly visible in each core from the distinctive red–brown colouration of the sediment. These sediments are composed of approximately 10% non-carbonate (bauxite) and have Fe contents of around 2–3000 μg/g (up to 7000 μg/g). The thickness of this upper bauxite-contaminated sequence increases down transect (approximately 18 cm in the shallowest core, to around 47 cm in the deepest core), and in each core overlies a sequence of 'clean' lagoon carbonates. These typically are poorly sorted carbonate sands with variable amounts of coral rubble. Down-core data on $CaCO_3$ and Fe content provide a chemical record of decreasing sediment contamination with depth, with the lower 'clean' carbonates composed of only around 2% non-carbonate and <700 μg/g Fe. Down-core sediment-constituent data also indicate significant changes in sediment production at the shallowest sites. At depths of 5 and 10 m, sediment assemblages have shifted from diverse assemblages of coral, mollusc, *Amphiroa* and *Halimeda* in the clean lagoon sands, to assemblages dominated by *Halimeda* and *Amphiroa* within the surficial sediments. At the deeper sites, no major down-core shifts in sediment constituents occur. These sites thus record a rather complex history of changes in sediment composition and chemistry. Clear shifts in chemistry and stratigraphy occur in all the cores and reflect progressive bauxite contamination in the near-surface horizons. These inputs, however, do not appear to have directly affected carbonate production, since the major constituent changes appear to be a response to more regional declines in coral community and reef status.

Keywords: Jamaica; coral reef; lagoon; carbonate sediment; bauxite; sediment contamination

1. Introduction

A high proportion of coral reef and reef-related (e.g., lagoonal) carbonate sediment is typically produced by organisms that live on or within the reef environment. Contributors include a wide range of skeletal organisms (e.g., corals, foraminifera, molluscs, echinoids) as well as a number of important algal groups that secrete calcium carbonate within their tissue structure (Scoffin, 1987). Such carbonate materials are released into the sediment either following death of the organism, or during post-mortem taphonomic alteration (e.g., Lowenstam, 1955; Folk, 1959; Swinchatt, 1965; Bathurst, 1975) and hence most carbonate sediments are produced essentially in situ, or at least within close proximity to the environments in which they are deposited. One important consequence is that the composition of a carbonate sediment can be regarded as being broadly representative of the community from which that sediment was derived. This has been demonstrated by numerous studies that have documented close linkages between reef-community assemblages and reef-sediment compositions across individual reef systems (Bathurst,

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1975; Gabrie and Montaggioni, 1982; Boss and Liddell, 1987a,b; Masse et al., 1989; Novak et al., 1992).

Such linkages between reef assemblages and sediment accumulation not only represent a basic premise for most carbonate microfacies work (Flügel, 1982), but also enable the utilisation of carbonate sediments as geoindicators of changes with respect to rates and styles of reef-carbonate production (Perry, 1996; Lidz and Hallock, 2000). Changes in carbonate production may be associated with either natural or anthropogenic disturbance events, or with subtle shifts in the environmental conditions associated with the reef setting (Hallock, 1988). In this respect, work on the composition of fore-reef sediments in north Jamaica has documented shifts in sediment assemblages following widespread and fundamental changes in reef-community structure (Perry, 1996). These changes have been linked primarily to the combined effects of severe hurricane damage, reduced herbivore abundance, coral bleaching, coral disease and elevated nutrient levels (e.g., D'Elia et al., 1981; Woodley et al., 1981; Goreau, 1992; Liddell and Ohlhorst, 1993; Hughes, 1994; Jackson, 1997; Lapointe, 1997; Greenaway, pers. comm.). Similarly, work on the Florida reef tract has documented major changes in sediment composition over several decades both in terms of bulk sediment facies (Lidz and Hallock, 2000), as well as the composition of specific sediment-producing faunal groups (Cockey et al., 1996). In these cases, changing patterns of carbonate production have primarily been linked to local changes in nutrient status that have increased the intensity of a key sediment-producing process, namely bioerosion.

Such changes, therefore, have the potential to follow both natural shifts in community state (e.g., linked to storm disturbance or coral bleaching) or those associated with anthropogenic activities (e.g., community shifts driven by over-fishing or nutrient inputs). One important potential cause of reef disturbance is sediment influx. Detrimental inputs may occur either episodically from river catchments (Mallela et al., 2004) or associated with anthropogenic activities (e.g., associated with land use change or nearshore dredging; Golbuu et al., 2003). Primary consequences of increasing sediment inputs can be to either increase sedimentation rates and/or turbidity regimes, both of which may be detrimental to reef-carbonate producers (Rogers, 1990). The former can result in smothering and burial of reef organisms (Cortés and Risk, 1985), the latter in reduced light penetration (Te, 1997). These changes may modify carbonate-sediment assemblages either directly by suppressing growth rates and the bathymetric distribution of specific carbonate producers (Acevedo et al., 1989), or by shifting the depth zones over which sediment-producing and taphonomic processes occur (Perry and Macdonald, 2002). Where sediment inputs are contaminant or metal rich, they may also fundamentally change sediment mineralogy and chemistry (Perry and Taylor, 2004).

Despite considerable research into the potential effects of sediment influx on reefs and coral communities, the impacts on reef-sediment assemblages and grain production have received comparatively little attention. Here we report on a study that examines down-core sediment facies in a reef-lagoon environment from Discovery Bay on the north coast of Jamaica. Sites within the bay have been subject to varying degrees of influence associated with inputs of fine-grained bauxite dust from a boat-loading terminal that was constructed in the mid-1960s. Hence the bay provides a record of fine-grained bauxite sediment input over a nearly 40-year period. Bauxite accumulation is concentrated within the deeper parts of the southern and south-western areas of the bay where significant dilution of surficial carbonate sediments, which now constitute up to 35 weight% non-carbonates, has occurred (Perry and Taylor, 2004). This paper describes temporal records of bauxite sediment accumulation within this previously carbonate-dominated lagoon system through the analysis of sediment cores recovered along a bathymetric gradient in the more heavily impacted regions of the bay. Principle aims of this research are to assess the extent to which inputs have (1) modified the sediment stratigraphy, and (2) altered sediment composition and chemistry.

2. Study area

Discovery Bay (latitude 18°30′N, longitude 77°20′W) is located approximately midway along the north coast of Jamaica (Fig. 1A). Much of the north Jamaican coast is associated with extensive fringing and bank-barrier reefs (Woodley and Robinson, 1977), and these are periodically interrupted by the presence of coastal embayments, of which Discovery Bay is an example. It is up to 1.5 km wide, reaches a maximum depth of 56 m (Fig. 1A) and is believed to be of karstic origin (Hine et al., 1991). The bay acts as a major sink for fine-grained carbonate sediment and sediment deposits within the bay are up to 40 m thick (Hine et al., 1991). There is no active terrigenous sediment input into the bay from fluvial sources, but relevant to this study is the presence of a bauxite-loading terminal in the south-west corner of the bay (Fig. 1A, C). Processed bauxite is an economic deposit composed primarily of oxides of aluminium and silicon, with high levels of iron and manganese oxides. Inputs of bauxite result both from wind blown materials that can be observed blowing off the boats during the loading process (typically blown downwind into the SW corner of the bay), and from episodic flushings of bauxite-rich slurry from the processing plant. The latter is believed to relate to a cleaning process within the plant and results in the distribution of a surficial layer of freshwater and fine bauxite which spreads as a red–brown coloured plume across the bay. This has been observed to spread at least halfway across the bay (pers. obs. April 1998) and to occur approximately every 6 months (R. Murray, pers. obs. 1997–2001). Once in the water column, the bauxite is subject to wave-driven currents (the dynamics of which are complex and vary with tidal state and depth; G. Cowie pers. comm. 2004) prior to settling out. These inputs increase turbidity and rapidly attenuate light (Perry and Macdonald, 2002). Sedimentation rates are spatially variable but in the vicinity of the study transect average $\sim 6\ \mathrm{mg\ cm^{-2}\ d^{-1}}$ at 5 m depth and $\sim 3.5\ \mathrm{mg\ cm^{-2}\ d^{-1}}$ at 15 m depth (Macdonald and Perry, 2003). A recent study of surficial sediment compositions undertaken within Discovery Bay (Perry and Taylor, 2004) identified significant bauxite accumulation across much of the southern section of the bay. 'Hotspots' of accumulation occur just to

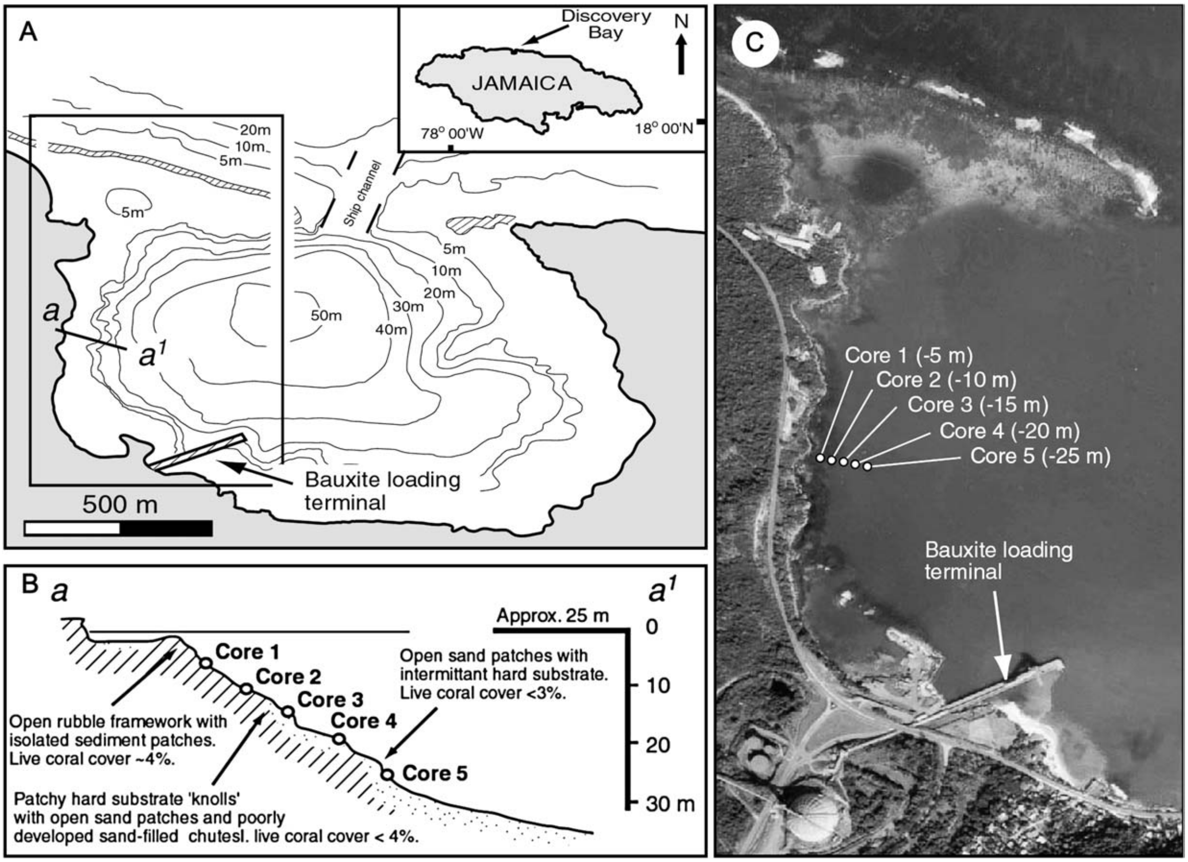

Fig. 1. (A) Map showing the location of Discovery Bay on the north coast of Jamaica and bathymetry of the bay. (B) Cross section along sampling transect a–a^1 in (A) showing the position of the core sites in relation to the reef structure. (C) Aerial photo of area boxed in (A) showing the location of the core sites in relation to the bauxite-loading terminal.

the north-east and north-west of the loading terminal where non-carbonate (bauxite) concentrations within surficial sediments reach 35 weight%.

On the basis of this previous work, a transect for the present study was established along a bathymetric gradient in the vicinity of the Columbus Park reef along the western side of Discovery Bay (Fig. 1A, C). A relict *Acropora palmata*/*Acropora cervicornis* reef framework exists in the upper 10–15 m at these sites (Wapnick et al., 2004) but presently supports a sparse coral community (live coral cover ∼4%) dominated by colonies of *Madracis mirabilis*, *Siderastrea siderea*, *Siderastrea radians*, *Porites astreoides* and *Montastrea* spp. (Macdonald and Perry, 2003; Fig. 1B). Below around 15 m depth the reef framework becomes increasing patchy and live coral cover remains low (∼3%; Macdonald, pers. comm. 2003). Common coral species at present are (in decreasing abundance) *Montastrea* spp., *Colpophyllia natans*, *M. mirabilis* and *Agaricia lamarki*. Below 20–25 m depth, the lagoon opens out into gently sloping (5–10°) sands and muds devoid of reef framework.

3. Methodology

To assess down-core (i.e., temporal) and spatial variations in bauxite sediment accumulation, cores were recovered from five sites along an E–W trending transect across the Columbus Park reef at depths of 5–25 m (Fig. 1B, C). PVC core tubes (1 m long, internal diameter of 64 mm) were emplaced by hand with the aid of a lump hammer and steel drive cap to a depth of approximately 80 cm. Penetration depths were marked for subsequent determination of compaction which, based on the uniformity of core penetration rates, were assumed to be uniform down core. Compaction in Cores 1–4 ranged between 25 and 35%, but reached 40% in Core 5. A rubber bung was placed on the top of each core prior to extraction and cores were capped at the base after extraction. Following recovery, cores were maintained in a vertical orientation and immediately returned to the boat for transport to the Discovery Bay Marine Laboratory.

Cores were extruded onto a section of core catcher and split in half using a wire slice. Digital photo composites and logs of each core were prepared prior to sub-sampling, and annotated with information about sediment colouration and composition, including information on common sediment constituents, coral clasts and burrow fills. Slices of sediment 1 cm thick were taken at 5 cm down-core (post-compaction) intervals (equating to a vertical spacing of around 6–7 cm in the decompacted sequence), providing samples of approximately 32 cm^3 from each sample horizon. These sub-samples were soaked in distilled water to remove salts (two separate washes over a 12-h period) and then soaked for 24 h in a 5% sodium hydrochlorite (commercial bleach) solution to neutralise organic material (this treatment has no discernible effect on carbonate mineralogy or grain texture; Gaffey and Bronniman, 1993). Samples were subsequently divided in half using a sediment splitter. One half of the sample was used to determine basic textural characteristics of the sediment, including mean grain size, sorting and weight% fines. Due to the presence of abundant fines in the samples, many of which had aggregated around grains during drying/transport, the sediment samples were wet sieved, with the weight% of samples retained in the >63 μm sieves recorded. Grain-size distribution of the remaining (<63 μm) size fraction sample was determined using a Beckman Coulter Counter following ultrasonic disaggregation and dispersion. The results of these analyses were combined using the computer programme GRADISTAT (Blott and Pye, 2001), from which values of mean grain size and sorting were taken (descriptive nomenclature of Udden–Wentworth is used throughout).

Sediment sub-samples were also used to determine total Fe content of the sediment (a major constituent of the bauxite; Perry and Taylor, 2004) and calcium carbonate ($CaCO_3$) content of both bulk and the <63 μm size fraction. Fe concentrations were determined by HNO_3 digestion followed by flame atomic absorption spectrophotometry; 0.5 g of air-dried sediment was digested in 10 ml of concentrated Analar HNO_3 at 85 °C for 2 h. The resulting solution was filtered through Whatman 42 filters and made up to 50 ml volume with deionised water. Analytical variability was tested by repeating the analysis on every third sample, with precision found to be within 2–3%. $CaCO_3$ was determined from sub-samples of known weight that were treated in a 2 M HCl solution until no discernible reaction with the carbonate could be detected. Samples were then filtered through pre-weighed Whatman 42 filter papers and oven dried. Replicate samples indicated that results were reproducible to within 3%. Carbonate content is given throughout as weight% of the original sample.

The second sediment split was used to determine the abundance of skeletal sediment constituents following the 'sieve-counting method' of Martin and Liddell (1988). Bulk sediment samples were split into the following size classes >4 mm, 2–4 mm, 1–2 mm, 0.5–1 mm, and 0.5–0.25 mm by wet sieving. The sediment composition of each size fraction was established by point counting 100 grains under a binocular microscope. Where fewer than 100 grains were present in a subsample, counts were based on a reduced figure. As in other studies (e.g., Gabrie and Montaggioni, 1982), binocular analysis of sediment fractions less than 250 μm was not undertaken due to the problems of accurately identifying grain type. Sediments were classified into the following categories: coral, crustose coralline algae, articulated red coralline algae (mainly *Amphiroa* sp.), *Halimeda* (a calcareous green algae), benthic foraminifera, encrusting foraminifera, molluscs (both gastropods and pelecypods), echinoderms, and other/unidentifiable. To determine abundance of individual sediment contributors at each site the total percentage abundance of each grain type was calculated by adding the relative proportion of grains found in each size fraction from each sample.

4. Results

4.1. Sediment-core stratigraphy and records of bauxite accumulation

Cores ranged in length from 75 to 85 cm (decompacted lengths; Fig. 2), all of which contained a clear visual record, evident from the distinctive red/brown colouration of the sediment in the upper portions of each core, of bauxite accumulation. A distinct cross-profile shift in bauxite deposition is evident, however, from the progressive increase in down-core thickness of the bauxite 'zone' with increasing depth along the transect (Fig. 2). In Core 1 (5 m depth) bauxite influence appears (from visual evidence) to extent to a depth of ∼18 cm, whilst in Core 5 (25 m depth) red/brown colouration of the sediment occurs to a depth of ∼47 cm. An interesting feature of the upper bauxite 'zone' in all of the cores was the presence of a clear internal stratigraphy, with the upper sections of each 'zone' characterised by a layer of highly fluid, dark red–brown fine-grained sediment. As with the overall depth of bauxite influence in the cores, so the thickness of this upper fluid layer also increases down transect (2–5 cm thick in Cores 1–3), reaching ∼15 cm in Core 5 (Fig. 2). Beneath this upper fluid zone, in all the cores a dark grey/brown horizon extends down core and grades eventually into apparently 'clean' carbonate sediments. This lower transitional zone from mixed carbonate and bauxite sediment, into 'cleaner' carbonates can appear either gradational (e.g., Core 2), abrupt (e.g., Core 4) or characterised by an inter-fingering of the two horizons (e.g., Core 3; Fig. 2). In some cores burrow fills, which contain more bauxite-rich sediment (and which thus stand out from the surrounding carbonates), are evident to depths of 50–60 cm (e.g., Cores 3 and 5; Fig. 2).

All of the cores penetrated the entire depth of bauxite influence at the respective sites and recovered 'clean' carbonates in their lower sections. These carbonate sediments lack a distinct internal stratigraphy and typically are poorly sorted sediments; larger carbonate grains, especially *Halimeda* and *Amphiroa*, as well as bivalve shells, are easily identifiable. The 'carbonate' sections also contain variable quantities of coral rubble. In the shallowest core (Core 1), most of the core below a depth of 20 cm contained abundant, well preserved and sparsely encrusted fragments of the branched coral *Acropora cervicornis* (Fig. 2). These fragments produce an unconsolidated framework that has infilled with sediments post-depositionally. *Acropora cervicornis* rubble, along with fragments of *Agaricia* sp. and *Siderastrea siderea* (?), were recovered in all of the remaining cores, but in much lower quantities than in Core 1.

4.2. Down-core shifts in sediment composition and chemistry

No consistent down-core shifts are evident across the cores in relation to sediment texture. In Cores 1 and 2 there is a slight down-core decrease in mean grain size and a down-core decrease in sorting (Fig. 3A). In Core 4, by contrast, there is a slight down-core increase in mean grain size (Fig. 3B), whilst

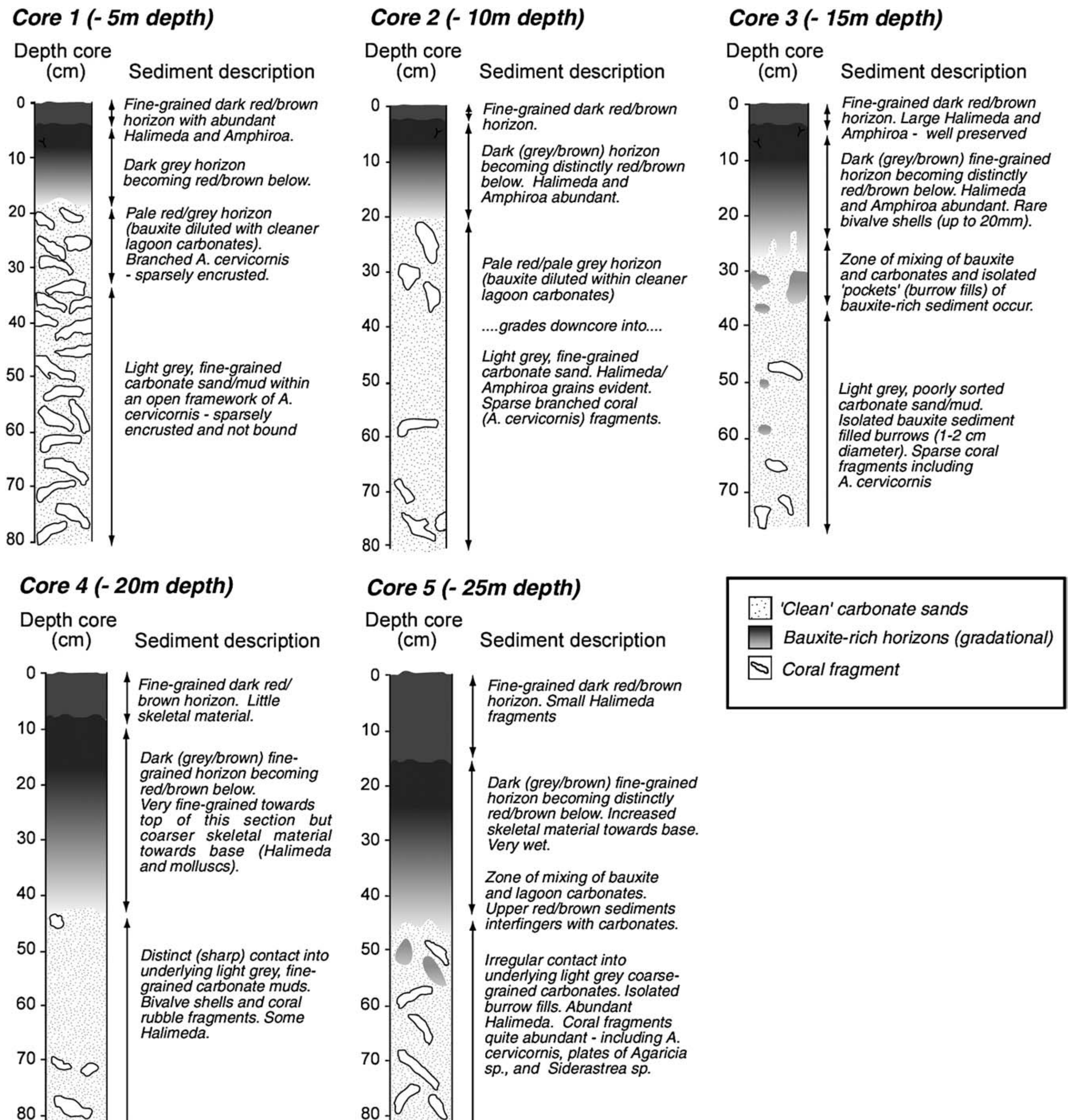

Fig. 2. Logs from the five sediment cores recovered from the Columbus Park reef. Note the progressive increase in the depth of the upper bauxite zone with increasing water depth. Vertical depths are for decompacted cores assuming uniform compaction.

sorting remains little changed. In Cores 3 and 5 there are no significant down-core changes in either parameter (Fig. 3A, B). These patterns are broadly mirrored in each core by the down-core changes in weight% fines (<63 μm). These increase in Cores 1 and 2, decrease down-core in Core 4, and remain little changed in Cores 3 and 5 (Fig. 3A, B).

Total $CaCO_3$ content within near-surface samples (0–5 cm down core) are ∼93–95 weight% in the shallower cores (Cores 1–3), and slightly lower, ∼88–92%, in the deeper cores (Cores 4 and 5; Fig. 3A, B). In Core 1 $CaCO_3$ content changed very little with depth (Fig. 3A). In the other cores, bulk $CaCO_3$ levels gradually increase down-core to around 98%. These trends are mirrored very closely by down-core increases in the $CaCO_3$ content of the <63 μm size fraction (Fig. 3A, B). Weight% $CaCO_3$ in the near-surface samples are, in all the cores, lower than those determined for the respective bulk sediment samples (∼85–88% in Cores 1 and 2, ∼80–86% in Cores 4 and 5; Fig. 3A, B), and increase down-core to ∼97–98 weight%. Near-surface (0–5 cm down core) Fe levels are in the range of 2–3000 μg/g, with the exception of Core 4

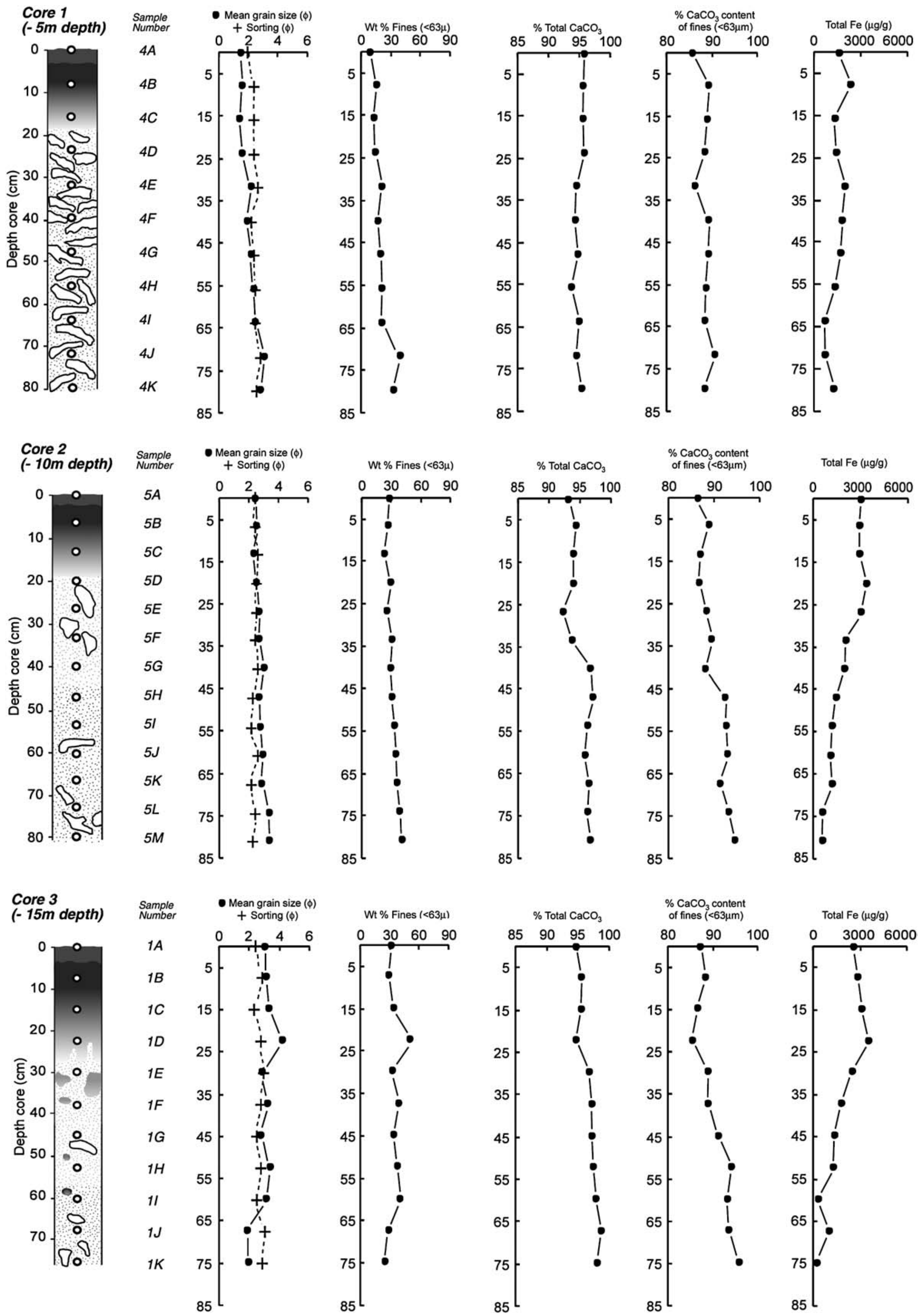

Fig. 3. Down-core plots for (A) Cores 1–3, and (B) Cores 4 and 5, showing trends in sediment texture and chemistry ($CaCO_3$ and Fe). Vertical depths are for decompacted cores assuming uniform compaction.

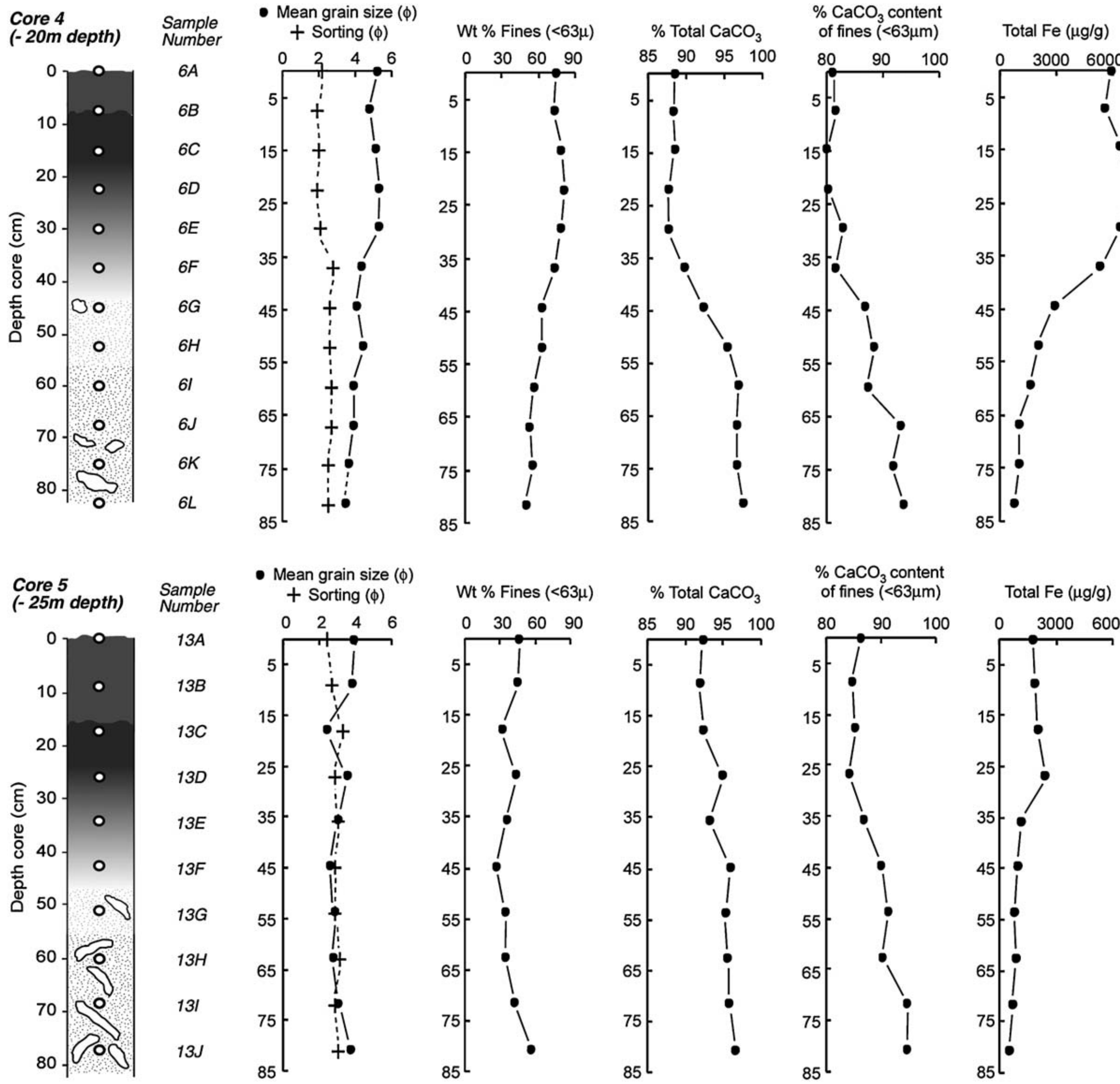

Fig. 3 (*continued*).

where levels of ~6000 µg/g were recorded. In contrast to $CaCO_3$, which mostly shows an increase down-core, total Fe exhibits clear down-core decreases in all of the cores. Fe levels typically decrease down-core to <700 µg/g, although in most of the cores, there is a slight increase in total Fe content below the immediate surface horizons. The depth of this 'peak', within the individual cores, increases down transect (e.g., Core 3 ~7 cm, Core 5 ~27 cm; Fig. 3A, B).

4.3. Down-core shifts in skeletal sediment assemblages

As with data on sediment texture and chemistry, down-core analysis of sediment composition reveals contrasting histories of carbonate-sediment accumulation at different sites along the transect. Sediments from all of the sites indicate that reasonably diverse carbonate-sediment assemblages characterise these areas of the bay, with coral, molluscs, *Halimeda* sp. and *Amphiroa* sp. all representing important sediment contributors (Fig. 4). Site-specific differences in sediment constituents do, however, occur. *Amphiroa*, for example, is a particularly important constituent at the shallower sites (5 and 10 m depth) with identifiable fragments attributed to the species *Amphiroa tribulus* and *Amphiroa fragilissima*, whilst molluscs contribute more significantly to the deeper (>15 m depth) assemblages (Fig. 4).

Analysis of constituent data from down-core sediment sub-samples from each of the sites reveals, however, rather different records of carbonate-sediment accumulation to those evident from analysis of sediment-chemical properties, where significant down-core changes occur in all of the cores (see above). In fact, the extent of down-core (i.e., temporal) changes in skeletal carbonate constituents gradually reduces down the transect. The most significant down-core shifts occur in Core 1 (5 m depth) and Core 2 (10 m depth). In these cores, sediment assemblages from the base of the cores (i.e., within the 'clean' carbonate facies) are characterised by diverse skeletal assemblages including ~40% coral, ~20–25% mollusc, ~10–15% *Amphiroa* and ~10–15% *Halimeda* (Fig. 4). Both of these cores exhibit a progressive

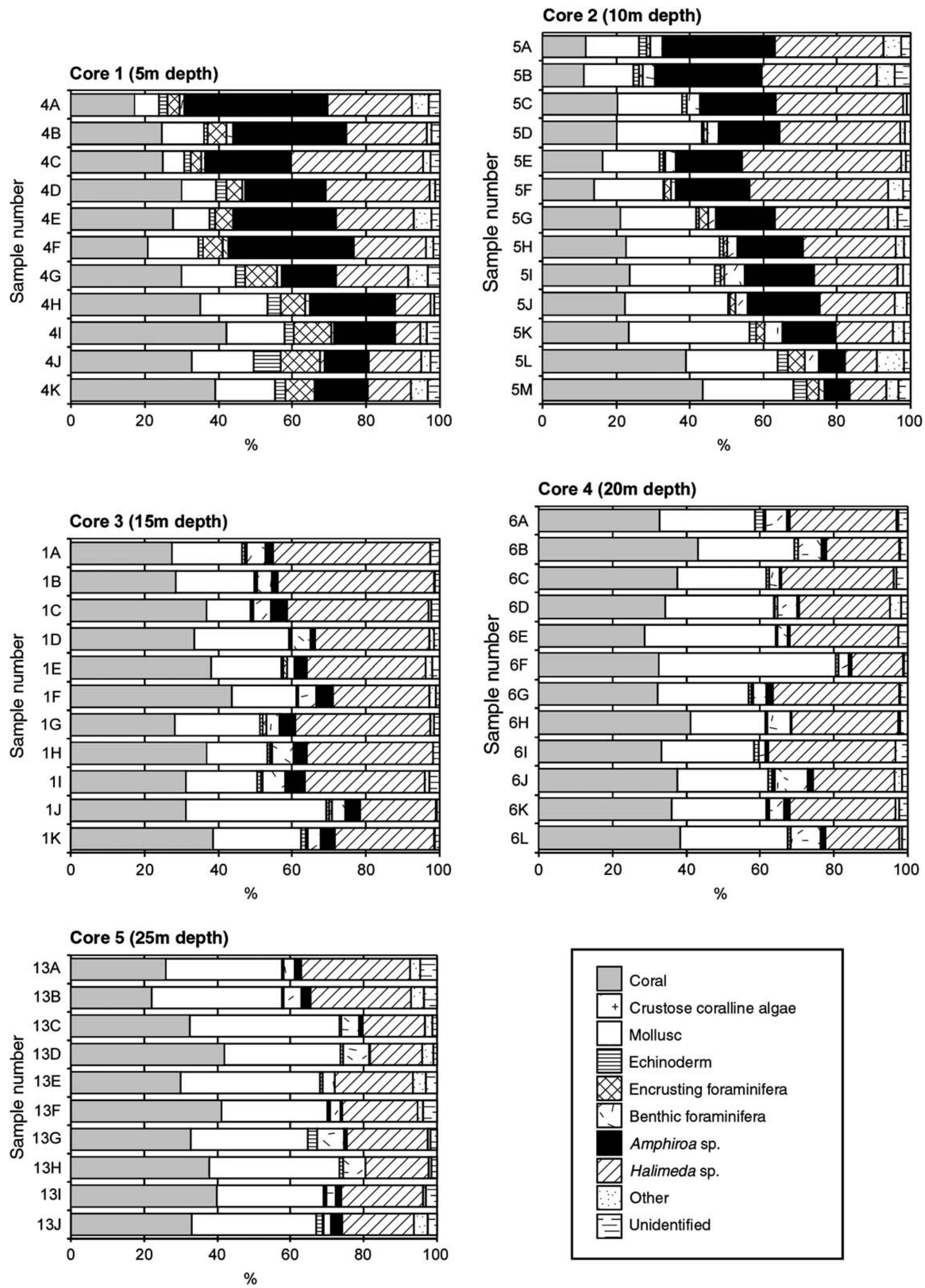

Fig. 4. Down-core plots showing changes in the relative percentage abundance of skeletal carbonate constituents (>250 μm sediment fractions).

and significant up-core shift in the relative abundance of these latter constituents, with the surface sediment layers presently dominated by ∼20–30% *Halimeda* and ∼30–40% *Amphiroa*. The abundance of coral fragments is, in contrast, significantly reduced (10–15%; Fig. 4). Of the identifiable species of these sediment contributors, no significant differences are evident down core; dominant species of *Amphiroa* being *Amphiroa tribulus* and *Amphiroa fragilissima*, while the dominant *Halimeda* are *Halimeda opuntia* and *Halimeda incrassata*.

In contrast, down-core sediment assemblage data from the deeper core sites (Cores 4 and 5; Fig. 4) indicate no significant compositional changes through time, and are composed of around 30–35% coral, 30–35% molluscs, and 20–25% *Halimeda* (mainly *Halimeda incrassata* and minor *Halimeda opuntia*). The contribution of individual constituents also varies little in relation to specific sediment-size fractions down core. At all depths through these cores, corals contribute primarily to the medium to fine sand fractions, molluscs and *Halimeda* to the medium to very coarse sand fractions. Core 3 (15 m depth) is composed of sediment assemblages that are essentially similar to those in the deeper cores. There is, however, evidence of a slight up-core shift in constituent abundance, seen as a general increase in the proportion of *Halimeda* (from ~30% to ~40–50%) and a reduction in coral (from ~30–40% to ~25%; Fig. 4).

5. Discussion

Cores recovered from sites across the Columbus Park reef in Discovery Bay provide a clear record of changes in lagoonal sediment accumulation. This is evident in relation to the stratigraphy of the cores and in terms of sediment chemistry. This major sedimentary change represents a shift from ‘clean’ lagoonal and reef facies in the lower sections of each core to near-surface horizons containing increasing concentrations of bauxite sediment. Such shifts in carbonate facies accumulation occur within the upper few centimetres to tens of centimetres in all of the cores, with the depth of down-core bauxite penetration increasing down transect (Fig. 2). This increase in bauxite accumulation with depth corresponds to previous observations of increasing bauxite content within surficial sediments, based on increasing Fe and reducing $CaCO_3$ content, with increasing water depth (Perry and Taylor, 2004), and which is attributed in large part to the increased settling potential of fines with depth (i.e., below wave base). Whilst previous work in Discovery Bay has thus shown clear evidence for the widespread distribution of bauxite within surficial lagoon sediments (Perry and Taylor, 2004), the present study documents a decadal timescale history of bauxite accumulation within the lagoon.

This visual record of sediment contamination is largely supported by down-core chemical data. Total Fe and the $CaCO_3$ content of the <63 μm sediment fraction provide the clearest evidence of down-core changes. Carbonate content, for example, increases from around 90% within near-surface sediments to around 98% in the lower sections of each core. Although the core transect does not intercept the areas of high non-carbonate content (up to 35 weight%) that were identified from central areas of Discovery Bay by Perry and Taylor (2004), the cores do provide a clear stratigraphic record of increasing bauxite accumulation. Within all of the cores (with the exception of Core 1), there are progressive down-core increases in the $CaCO_3$ content of the <63 μm fraction, and a decrease in total Fe, reflecting progressively lower levels of bauxite contamination. These data indicate, however, a more gradational down-core shift in sediment chemistry than that implied by the visual record (see Fig. 2). Down-core shifts in total $CaCO_3$ occur but are not as marked as for the other parameters. Whilst this may seem somewhat surprising, the bauxite entering the system is composed of material that falls within the <63 μm fraction (Perry and Taylor, 2004). Hence, it is within these finer sediment fractions where the major carbonate dilution is occurring.

An interesting feature of the bauxite-rich upper sediment layers is the presence of an apparent sediment stratigraphy. The uppermost layers, in all of the cores, comprise a zone of highly fluidised sediment that has a distinctive red–brown colouration. This appears to represent a layer of highly flocculated and semi-suspended sediment that forms an interface zone between the underlying (more consolidated) sediment and the overlying water column. This ‘layer’ is apparent when diving these sites in the form of a very easily resuspended surface horizon that we interpret as a mobile, benthic layer of flocculated sediment. This may form a zone of semi-continuous sedimentation, the dynamic nature of which may be maintained by the sediment resuspension associated with active infaunal and epifaunal sediment reworking (e.g., Rhodes, 1967, 1974; Aller and Dodge, 1974). The depth of this layer increases in the deeper cores and is underlain by a more consolidated sediment layer within which the higher Fe levels occur. This may, therefore, represent a zone of concentration beneath the more fluidised surface layers.

Down-core there is a gradation towards cleaner carbonate that often visually appears abrupt, but in fact seems rather more transitional based on the sediment chemistry. This most probably reflects the effects of more or less continuous bioturbation that has likely occurred throughout the history of bauxite accumulation. The activities of epi- and infaunal organisms are well known to mix and homogenize sediments throughout their depth zones of activity (Rhodes, 1967; Aller and Dodge, 1974). Shallow infaunal molluscs and echinoids actively rework the surface layers at present (even at the deepest sites) and open burrows were observed at most of the coring stations. Hence, during the earliest phases of bauxite input in the mid-1960s when the loading terminal was constructed, biogenic mixing with essentially clean carbonates resulted in very low levels of contamination as bauxite was mixed over several centimetres of the near-surface sediment layer. However, as bauxite inputs have persisted over the years and its concentration in the sediment increased, progressive dilution of the carbonate substrate has occurred. Previous sedimentological (Wright, 1977) and geochemical (Nolan, pers. comm.) studies conducted in the bay in the early 1970s and 1980s provide some evidence to support this view. Where same-site comparisons are possible, three-fold increases in Fe levels (~1200 ppm to 4000 ppm) and a doubling in the non-carbonate composition of the <63 μm sediment fractions are evident.

Changes within the sediment facies are evident not only in terms of the finer sediment fractions, but also in relation to the abundance of coral clasts (>64 mm) within the cores. Abundant coral material occurs in the lower sections of each core, but is noticeably absent within the near-surface sediment horizons (see Fig. 2) and there are two potential causes of this. One explanation may relate to the effects of the bioturbation outlined above, since some bioturbators (such as the infaunal shrimp *Callianassa*) are known to actively rework coarser skeletal fragments to depth (see Tudhope and Scoffin, 1984). However, *Callianassa* burrows are relatively rare at many sites and thus seem, from visual observations, to be an unlikely cause of such widespread reworking. In any case, the current status of the coral communities at these sites (see below) would suggest this is not an on-going process. A second, potential explanation is that this apparent shift in coral clast abundance reflects a change in carbonate production.

Prior to the early-1980s, a thriving shallow water reef was developed in the vicinity of Columbus Park characterised by typical (although bathymetrically compressed) north Jamaican coral communities. *Acropora palmata* (0 to ∼1.5 m depth) and *Acropora cervicornis* (1.5 to ∼12 m depth) dominated much of the shallower reef, with colonies of *Colpophyllia natans*, *Montastraea* spp., *Siderastrea siderea* and *Agaricia* spp. dominating below ∼12 m depth (Wapnick et al., 2004). Little of this coral community remains (pers. obs.) and live coral cover on the Columbus Park reef is presently very low (∼3–4%; Macdonald, pers. comm. 2003). Since the die-off and degradation (to rubble) of the branched coral communities, substrate accumulation has been dominated by carbonate and bauxite sediment that now forms a horizon overlying the relict *A. cervicornis* framework. A clear sedimentary record of these previously flourishing branched coral communities is preserved in the lower sections of Core 1 and, to a lesser extent, Core 2 (Fig. 4).

The timing of this *Acropora cervicornis* die-off event at the Columbus Park sites has been discussed by Wapnick et al. (2004, p. 356). Although these branched colonies appear to have been largely unaffected by Hurricane Allen, which decimated branched coral communities along north Jamaican reef front sites in 1980, surveys conducted in 1982 indicated that although these colonies were dead, they remained in growth position. Subsequent surveys, however, indicate that these dead in situ stands had been reduced to rubble by 1987 when abundant rubble material was observed to litter the reef surface at these sites (Wapnick et al., 2004). The generation of this uppermost layer or sequence of *A. cervicornis* rubble thus appears to-date from sometime in the period 1982–1987, i.e. considerably after bauxite inputs were initiated. Consequently, the shifts in sediment stratigraphy recorded at these sites do not entirely appear to be a direct response to the sedimentary changes linked to bauxite inputs, but rather to reflect shifts in coral community composition, and which have been linked to a more general decline in the status of most north Jamaican reefs (Liddell and Ohlhorst, 1993). In the intervening years very different deposits have formed above this carbonate sediment and coral rubble facies, with the chemistry and composition of the overlying sediments (discussed above) recording evidence of a significant shift in lagoon sediment accumulation.

Whilst data on sediment chemistry provide a clear record of increasing concentrations of bauxite within the sediments at these sites, and changes in coral rubble abundance illustrate the effects of a regional decline in reef-community status, a rather more complex picture emerges in terms of changes in carbonate-sediment constituents. Up-core analysis of sediment samples from the shallower sites (Cores 1 and 2) record evidence of clear shifts in constituent abundance. This is evident as a reduction in coral, and the increased abundance of *Halimeda* and *Amphiroa*. These changes can be interpreted as representing actual changes in sediment input because of the presence of the more recent bauxite-rich layers that are so clearly defined at the top of each core sequence, and which suggest a lack of large-scale sediment mixing. It is clear, however, that these changes do not simply coincide with the in-core transition to bauxite-rich sediment and are thus unlikely to be linked directly to bauxite inputs into the environment. Hence these changes are interpreted as reflecting an on-going shift in sediment production linked to the broader reef-community shifts previously described. At these shallower sites, coral cover is very low and much of the previous coral framework has, or is becoming, progressively buried by sediment, thus framework contributions from processes such as bioerosion are largely shut off. In contrast, much of the shallow reef surface is now overgrown by colonies of *Amphiroa* and *Halimeda* (pers. obs.), and it is these prolific sediment producers that now represent the major shallow water sediment constituents.

Sediment samples from the deeper core sites, in contrast, indicate little or no change in the relative abundance of the dominant sediment constituents (mainly coral, molluscs and *Halimeda*). This is despite the fact that these are the cores which exhibit the most significant down-core bauxite penetration and the highest levels of Fe. Hence, whilst the chemical composition of the sediments has altered, the composition of the constituent skeletal carbonates has not. Sediments at these sites are likely to represent a combination of those produced in the immediate vicinity of the areas of accumulation, and those transported from shallower reef sites. Coral framework becomes increasingly patchy with depth at Columbus Park, but probably remains important as a local source of finer-carbonate material (probably derived from bioerosion; see Macdonald and Perry, 2003). Molluscan in- and epifauna are also common and *Halimeda* occurs to depths of ∼25 m at these sites. In addition, evidence of slumping occurs in most of the channels that form on the 'reef-front' and represents a mechanism for down-reef sediment transport. These different sediment sources, in combination with the effects of on-going sediment bioturbation, may produce rather mixed sediment assemblages which have not yet responded to the community shifts evident at the shallower sites. In combination with data from the shallower sites, it is therefore suggested that bauxite sediment inputs have had little direct effect on carbonate-sediment production, at least as major drivers of reef-community change. Rather it is large-scale coral community decline at these sites (linked to various causal factors) that appear to have caused a shift in the abundance of carbonate constituents in the sediment facies.

6. Conclusions

Cores recovered from a transect across Columbus Park reef in Discovery Bay show clear evidence for a major temporal shift in carbonate-sediment accumulation. Inputs of bauxite sediment over the last 40 years are recorded as clear horizons in the upper portions of each core and overlie essentially 'clean' carbonate facies that often contain abundant coral rubble. Whilst there is clear evidence for major chemical shifts in the sediment in terms of reduced $CaCO_3$ levels and an increase in Fe in the sediment, a more complex picture emerges in terms of skeletal carbonate constituents. At shallow sites (5 and 10 m) significant up-core changes in constituent abundance are recorded, but at the deeper sites (15, 20 and 25 m) such changes are insignificant. This lack of a clear signal, combined with the fact that the constituent changes are negatively correlated with the sites of increasing bauxite accumulation, suggest that whilst bauxite inputs have significantly modified the basic chemistry of the sediments, there has to-date been no direct effect on carbonate-sediment production. Rather, these changes are attributed to broader reef-community shifts that reflect a complex history of reef ecosystem decline.

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